US Patent application 10/596,847 – Rule 1.132 Declaration

Background

The main aim of this document is to clarify the role of expanded mesh in novel laminates (here referred to as the 'ELACO laminates') presented in the patent application US 10/596,847 subject to USPTO examination and to stress some key aspects of the laminate behaviour and properties that are a consequence of the mesh presence.

It is in author's professional opinion that expanded mesh, as a dissipating element, provides vastly different dynamic and quasi-static fracture properties of the laminate when compared to properties that could be achieved by using any other type of metal mesh in the same laminate configuration.

I gathered an intimate knowledge of the ELACO laminates by conducting a series of material testing experiments and by devising some of the preliminary mathematical and numerical models of ELACO laminates.

My professional background is in aerospace engineering with a PhD in composite materials fracture mechanics, obtained from The Australian National University, where all ELACO laminate testing was conducted.

Expanded mesh geometry

This section elaborates some of the main geometric parameters of an expanded mesh. I use Expamet 602A aluminium expanded mesh as an example. For the sake of simplicity I will assume that the ELACO concept denotes that the laminate is formed around a single mesh positioned in the centre. In a more general approach, the ELACO concept does not preclude using multiple meshes as dissipating elements. Basic geometry parameters of an expanded mesh are depicted in Figure 1.

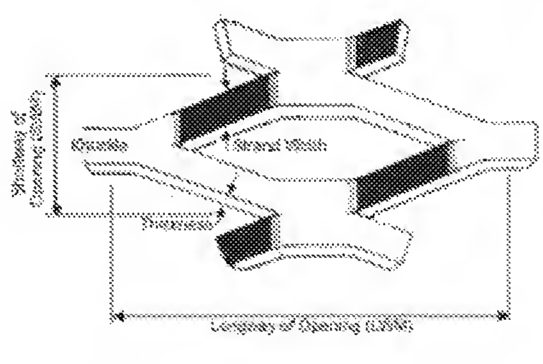

Figure 1. Expanded metal mesh geometry

Although this basic set of geometrical parameters indicates that the geometry of the top and bottom side of the mesh should be the same, this is not the case since the radii on the cutting tool, used for

forming the mesh, are not equal. The consequence of this is a formation of the sharp and blunt sides of the mesh as illustrated in Figure 2 and Figure 3.

The mesh surface is protected from corrosion by clear anodizing process, which improves bonding to the rest of the laminate.

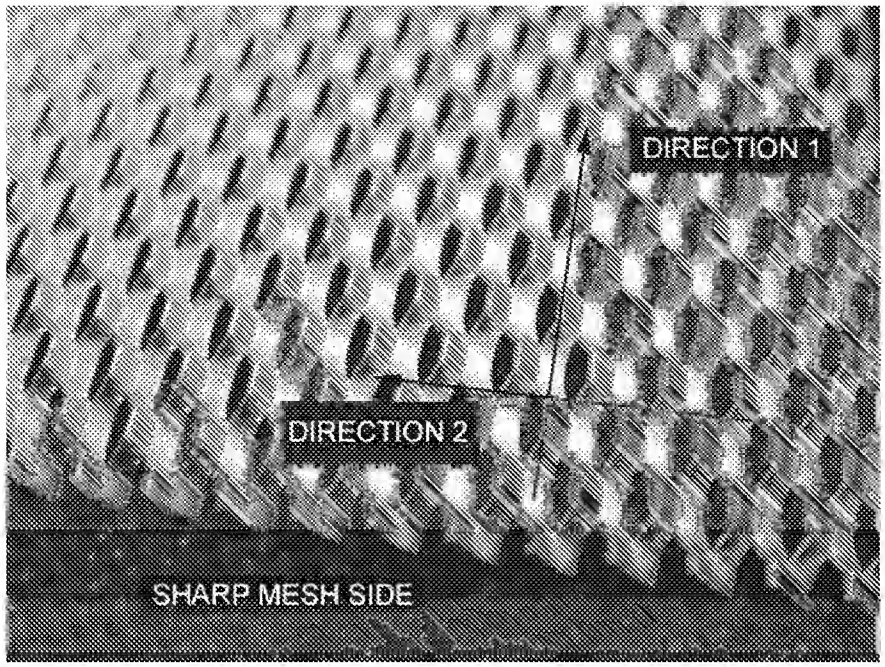

Figure 2. Mesh – sharp side

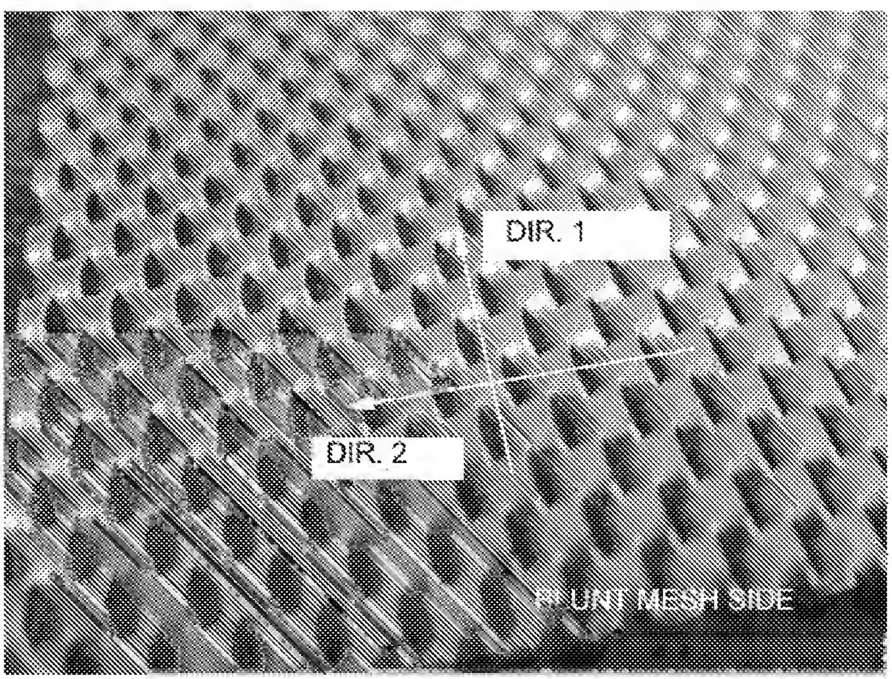

Figure 3. Mesh – blunt side

In all ELACO laminates the mesh is a dissipating element and the region of the laminate that it occupies is defined, for the purpose of clarity in this Declaration, as the ***core*** region. The reason for this designation is due to a clear resemblance between sandwich composite laminates and ELACO laminates. Both clearly have a distinctive central region that has different properties than the outer parts of the laminate (denoted in this text as the 'laminate skins' and consisting of 'outer layers' and 'inner plies' immersed in resin, as defined in the patent application). The properties of the ***core***, largely driven by the properties of the resin trapped inside the mesh (dissipating element) structure, strongly influence the properties of the laminate as a whole, regardless of the layup and material combinations used for the 'laminate skins'. This will be elaborated in more details in the following sections.

Several key points about the mesh geometry should be stressed at this point:

1. Expanded mesh is a monolithic 3D structure created by cutting and plastically deforming a flat sheet of metal. In this process the material properties of the base flat sheet are modified by the strain hardening process. The main consequence of this process is an increase in ultimate strength of the newly formed expanded mesh when compared to the base sheet strength.
2. Every single mesh opening is a pyramid-like structure that is inter-linked with adjacent openings. Any perpendicular loading to the mesh (being dynamic or quasi-static) is dissipated and redirected in all directions equally due to the 3D nature of the mesh. This is a complex concept to be illustrated, hence a simplified illustration that was submitted with the original patent application. While the illustration is useful in conveying a basic principle of force redirection in one dimension, it does not accurately illustrate a far more complex process of force dissipation that is present in the case of expanded mesh.

The role of polymeric resin

The primary role of the resin in ELACO laminate is to bind all parts of the laminate together. The resin is not optional or secondary in ELACO - it is absolutely crucial. Under the impact loading, resin in the ELACO laminate transfers the load from the outer skins to the laminate core and the dissipating element. The bending of the laminate under the loading stresses the 'laminate skins' in compression and tension while the dissipating element (i.e. expanded mesh) is under the pure shear loading. This shear load is created in the resin that is situated around the dissipating element and transferred to the dissipating element through a bonded interface between the dissipating element and the resin. In addition to this, the mesh has to accept localised loading around the area of the immediate impact. These loads are purely compressive and they are absorbed by the local plastic deformations of the mesh pyramid-like 3D structure. This local deformation is the effect of the force dissipation process, where a perpendicular load is transformed and redirected in all directions that are parallel to the laminate impact plane. Finally, the resin around the impacted zone is crushed and deformed to the stress level when the interface between dissimilar materials (i.e. mesh and the resin) starts to delaminate. The failure of the mesh/resin bond has to follow the 3D structure of the mesh and as a consequence, it forms a very uneven rough surface that by itself is quite resistant to

further shear deformation of the laminate core. The cracking of the resin absorbs large amounts of the impact energy while after cracking the rough surface resists further delaminating through increase in friction between the delaminated faces.

Energy absorbing mechanisms in ELACO laminates

The impact energy absorption mechanisms in ELACO laminates are, summarised, as follows:

- The laminate skins (consisting, as explained before, of the outer layers and fibre reinforced inner plies) receive the first impact and maintain the structural integrity of the laminate by providing sufficient stiffness. Their global laminate elastic deformation absorbs the first stress wave. The secondary role of the laminate skins under the immediate impact is to resist penetration of the impactor.
- The remaining impact energy is transmitted to the dissipating element which absorbs the impact energy by plastic deformation of its 3D pyramid-like form. This deformation dissipates the relatively localised impact energy to a much larger area through the force redirection effect explained in the present (ELACO) patent application.
- The resin serves as a n essential medium for load transfer in this process. Furthermore, the resin cracking, delaminating and deformation follows the mesh's 3D boundary and absorbs the remaining transmitted impact energy. Finally, even the delaminated surface absorbs deformational energy by resisting any shear motion of the laminate core through increase in friction and converts the remaining energy into heat.

All these energy absorbing mechanisms work in synergy. It is absolutely necessary that all parts of the ELACO laminate (i.e. outer layers, inner plies, dissipating expanded mesh element and resin) are present in the laminate in order for all of them to work simultaneously and maximize the energy transmission and absorption.

These failure mechanisms are similar under quasi-static loads and this was observed and recorded during the test program of the ELACO laminates. The only difference between the dynamic and static failure events is in the origin of the failure initiation. While the impacted laminates always develop the first failure under the immediate impact zone, statically loaded laminates fail at the free-edge. This failure is illustrated in Figure 4. Under testing, the laminate (ELACO) sample was subjected to a bending load in the standard 3-point bend fixture.

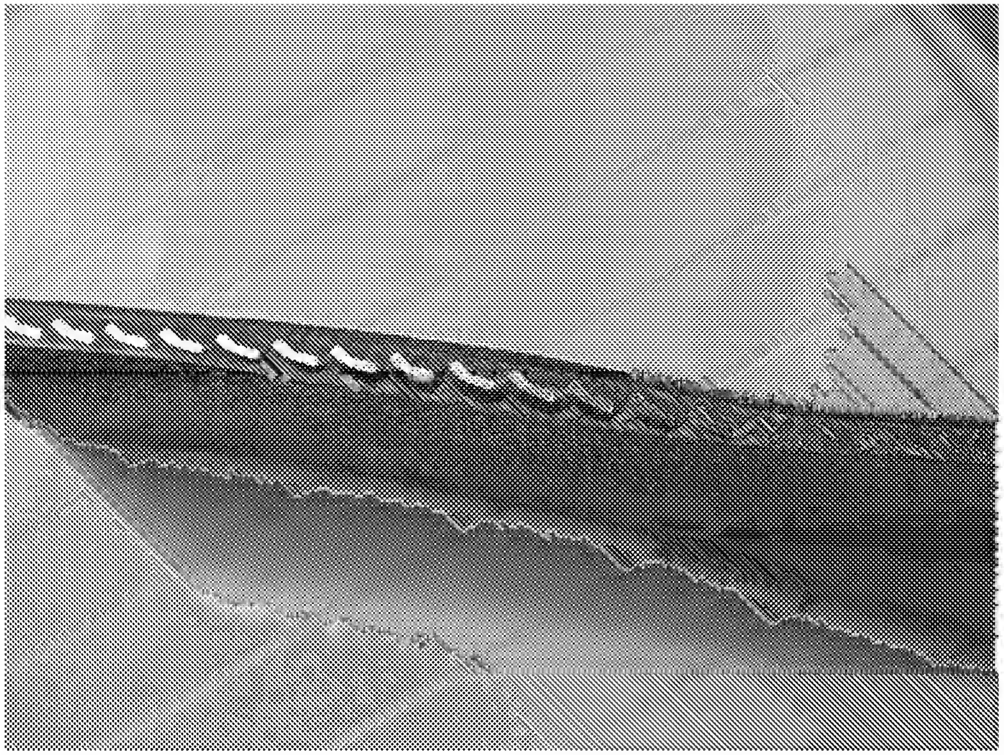

Figure 4. ELACO 3-point bend test (presented after impact) – expanded mesh controls the crack path

It can be seen that the laminate skins did not fail during the test, apart from minor damage on the compression side under the load nose. The main failure was a shear failure that developed into a delamination crack along the 3D mesh face. It should be noted that the mesh is the same one that is depicted in Figure 2 and Figure 3. The main cracked face, although it appears as one dimensional zig-zag line, in fact is a very complex three-dimensional face that closely follows the 3D shape of the mesh.

This failure, although initiated by a far-field shear stress field, developed by a coalescence of multiple micro-cracks that developed under local tensile stress field. This is a known failure mode of composite materials under flexural loading. However, it is obvious that aforementioned local tensile field was strongly influenced by the mesh. The initial tensile cracks developed due to stress concentrations around the edges of the mesh profile, as illustrated in Figure 5 (points marked with A).

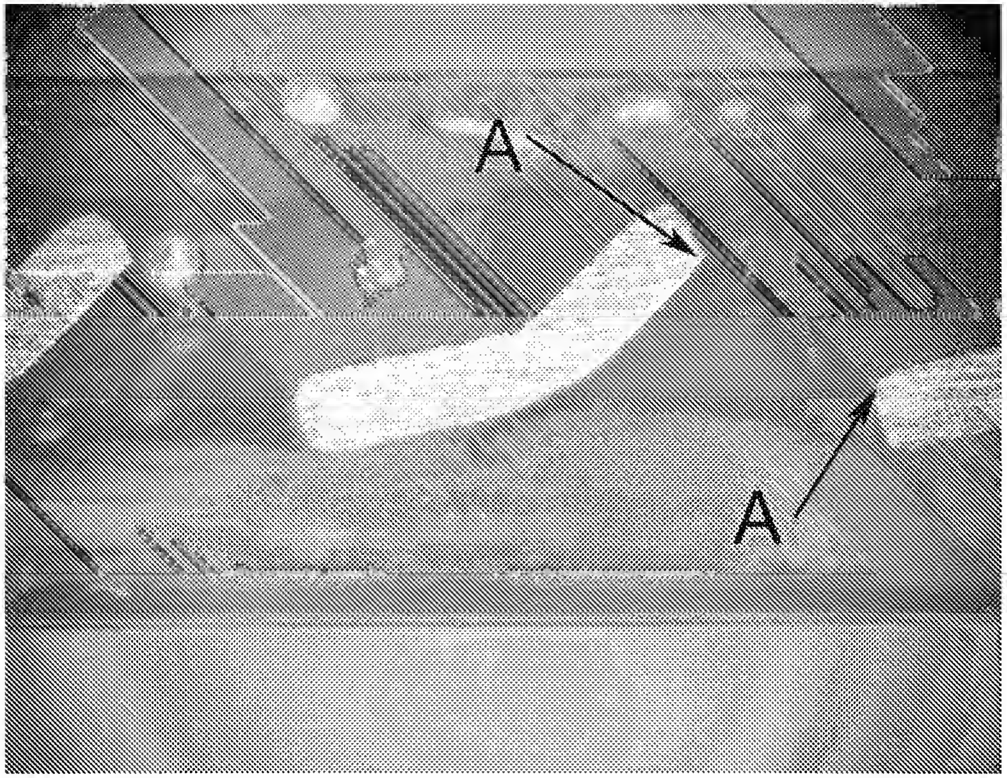

Figure 5. Microscopic photograph of a tested ELACO laminate showing stress concentration points at expanded mesh profile corners

Once the crack bridges the gap between two mesh openings, it continues along the mesh until it reaches the peak of the mesh 3D profile where it joins with another crack. The main improvement and increase in energy absorption is due to a longer crack path if compared to a similar laminate without the mesh, where delamination would propagate in a straight line along a resin/fibre interface. The 'kinked' crack path formation slowed down the whole failure process and allowed the laminate to achieve large deformation levels without any sign of catastrophic failure. This was clearly an unexpected result specific to the laminate structure presented in this patent application, which utilises the expanded mesh as its dissipating element. Such unexpected result is of such significance that it renders the novel technology presented in this application as non-obvious.

Conclusion

From all of the above it is evident that the three-dimensionality of the dissipating element in the present patent application is the key to achieving the maximum impact energy absorption of the present invention, combined with all other elements of the respective (ELACO) laminates, as explained above.

The patent examiner compared the ELACO laminate with the structure presented by Calfee, who teaches the use of corrugated metal sheets as dissipating elements. Even if one ignores the lack of

the binding resin in that patent, which is crucial for the proper load transfer, the fact is that simple corrugated sheets are structures deformed in two dimensions. The third dimension opens a very low resistance path for the crack growth. This fact changes completely the behaviour of the structure under impact load when compared to the ELACO laminate. The two laminates, one presented by Calfee and the ELACO one, would have different structural response under the same loading conditions and consequently, different failure mechanisms and modes of energy absorption. Even if one would use a binding resin with the Calfee's laminate, the main failure mode would always be a catastrophic fast delamination along the direction parallel to the corrugations of the dissipating element. The Calfee laminate would absorb energy primarily through deformation of the dissipating elements with very little engagement of the surrounding structure and resin (if used). The Calfee laminate would dissipate impact forces only along one direction - the one perpendicular to the corrugations. On the other hand, the ELACO expanded mesh dissipates the impact multi-dimensionally and engages the matrix and its failure processes as an effective energy absorption mechanism.

Structures presented by Hollis and Chavannes contain the same corrugated dissipating elements presented by Calfee with an addition of wire-mesh elements. Even when used in combination, a flat wire mesh and a corrugated structure do not form a monolithic three-dimensional structure that can absorb and redirect the impact load multi-directionally. The wire mesh that is presented by Hollis and Chavannes serves to prevent the penetration of the laminate under impact. This mesh does not provide any impact force redirection effect. The wire mesh provides the immediate penetration protection by being loaded in tension by the impact force. It acts in the same way as the outer skin layers of the ELACO laminate act. Therefore, the wire mesh is NOT a dissipating element, it can only be treated as a component of the laminate skins. Both Hollis and Chavannes still rely on a corrugated structure to act as a dissipating element and it was already stressed that the force dissipation is in that case acts only along one direction and opposed to the ELACO multi-directional dissipation.

Final observations

I would like to stress once again that the combination of all elements used in the ELACO laminates: laminate skins (consisting of outer layers and inner plies), the central dissipating element and the binding resin, is absolutely necessary to obtain the *synergic effect* which maximises the impact energy absorption to an unexpected and non-obvious level. Furthermore, in order to optimize an ELACO laminate, one needs to consider and understand all energy absorbing mechanisms combined with the scale of the loaded structure and the nature of the impact event. It required many hours of laboratory testing and numerical simulations to fully understand some of the energy absorbing mechanisms present in the ELACO laminates. Namely, the scale effect; the effect of the laminate thickness and the required laminate skin reinforcement, which drives the stiffness of the structure. It is not possible for someone with ordinary skills in the art to achieve this by merely combining all the materials ad-hoc without fully understanding the complex failure mechanisms of this structure.

Finally, the strength of this invention is in its novel use of the expanded mesh as its dissipating element, in combination with the reinforcement inner plies and the outer layers, all immersed in resin. It is my professional opinion that this technology provides a novel and alternative solution to an existing need in the composite material art and provides a novel approach to solving common

problems apparent in the known laminates, including the cited prior art. None of the patents that were compared to ELACO contain all aspects of this material, and it is precisely this completeness of the ELACO idea that makes it so effective in serving its purpose of resisting impact loading.

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Canberra 03/10/2011